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Regional multi-fluid-based geophysical excitation of polar motion

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Abstract By analyzing geophysical fluids geographic distribution, we can isolate the regional provenance for some of the important signals in polar motion. An understanding of such will enable us to determine whether certain climate signals can have an impact on polar motion. Here we have compared regional patterns of three surficial fluids: the atmosphere, ocean and land-based hydrosphere. The oceanic excitation function of polar motion was estimated with the ECCO/JPL data – assimilating model, and the atmospheric excitation function was determined from NCEP/NCAR reanalyses. The excitation function due to land hydrology was estimated from the Gravity Recovery and Climate Experiment (GRACE) data by an indirect approach that determines water thickness. Our attention focuses on the regional distribution of atmospheric and oceanic excitation of the annual and Chandler wobbles during 1993-2010, and on hydrologic excitation of these wobbles during 2002.9-2011.5. It is found that the regions of maximum fractional covariance (those exceeding a value of $3 \cdot 10^{-3}$) for the annual band are over south Asia, southeast Asia and south central Indian ocean, for hydrology, atmosphere and ocean respectively; and for the Chandler period, areas over North America, Asia, and southern South America; and scattered across the southern oceans for the atmosphere and oceans respectively.

Keywords atmosphere · ocean · land hydrosphere · polar motion

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1 Introduction

It is already known that changes of the mass distribution of the atmosphere and the ocean are the essential sources for the excitation of changes in the movement of the pole, in both the seasonal and Chandler bands of the spectrum (Eubanks, 1993; Gross, 2000; Brzeziński and Nastula, 2002; Brzeziński et al., 2002; Gross et al., 2003). We note too that changes of the angular momentum generated by the motion terms, namely the atmospheric winds and oceanic currents, may also play a role in polar motion, though of smaller magnitude. Here we do not look however at the motion term distribution because most regional Atmospheric Angular Momentum (AAM) terms cancel other AAM terms in different regions, and also most Oceanic Angular Momentum (OAM) terms cancel each other (Nastula et al., 2012). Variations of the pressure term of the AAM over central Eurasia primarily, and North America secondarily, are responsible for much of the power in the polar motion excited by the atmosphere (Nastula and Salstein, 1999; Nastula et al., 2003). Likewise, the oceanic excitation of polar motion has sources in the Southern Ocean, South and North Pacific, and North Atlantic containing strong fluctuations in both the mass term, as evidenced by bottom – pressure signals, and the motion term, noted by current strength (Ponte and Stammer, 1999; Nastula et al., 2003; Ma et al., 2007, 2009; Nastula et al., 2012).

Hydrological excitation functions of polar motion from land-based hydrology, when determined from models of the hydrosphere, are dominated by seasonal, mostly annual, variability. In these hydrological excitation functions (Hydrological Angular Momentum – HAM), prominent maxima are situated over the equatorial monsoonal regions of the Amazon, India, central and southern Africa and northern Australia (Nastula and Salstein, 2011).

The monthly time step of most of the hydrological models restricts analysis to signals of seasonal and longer period. Large hydrological variability in equivalent water thickness occurs in the lower latitudes over Southeast Asia, South Asia, and the South American Amazon regions. These regions remain important even when multiplied by the polar motion transfer functions, with the exception of the band very close to the equator.

An indirect approach for estimating land hydrology is one that determines equivalent water thickness (EWT) based upon solutions from the Gravity Recovery and Climate Experiment (GRACE)(Tapley et al., 2004). The analysis of the GRACE mission gravimetric data is carried out by several centers: Centre for Space Research (CSR), GeoForschungsZentrum (GFZ), Jet Propulsion Laboratory (JPL) and Centre National d'Etudes Spatiales / Groupe de Recherche en Geodesie Spatiale (CNES / GRGS), based on several releases. The differences in the hydrological results among models and between models and the GRACE – based solution are still considerable, and need to be reconciled to better understand the uncertainties involved (Nastula et al., 2011; Seoane et al., 2011). In this paper we used the EWT fields from CNES/GRGS which are given at 10–day intervals (Bruinshima et al., 2010).

We present here an intercomparison of the excitations of polar motion caused by the three geophysical fluids, as based on a number of models. Furthermore, we concentrate on two spectral ranges, the annual, and the band around the Chandler (roughly 14 – month) wobble.

2 Data and methods

2.1 Data

The so – called geodetic polar motion excitation functions χ_1 and χ_2, describe the effective changes in the angular momentum components about two equatorial axes conventionally taken to point towards the Greenwich and 90^o E meridians, respectively. The International Earth Rotation and Reference Systems Service (IERS) provides χ_1 and χ_2 series computed from the combined time series C04 of the Earth Orientation Parameters (EOP) at daily intervals, and we are concerned here with the pole coordinates x and y. The geodetic polar motion excitation from the IERS C04 series of polar motion is consistent with the classical Barnes et al. (1983) formulation, computed according to the methods of Wilson (1985).

Regional values of the atmospheric excitation function of polar motion were computed from the National Centers for Environmental Prediction (NCEP) the and the National Center for Atmospheric Research (NCAR) – NCEP / NCAR reanalysis fields (Salstein et al., 1993). The basic data include 6 – hourly surface pressure values on a $2.5^o \times 2.5^o$ latitude – longitude grid; by the National Oceanic and Atmospheric Administration Operational Model Archive Distribution System (http: // nomad3.ncep.noaa.gov). The regional atmospheric excitation functions computed by the classical Barnes et al. (1983) formulation were averaged to a 10 – day solution over the period January 1993 – December 2010 for consistency with the oceanic excitation function data. Here we computed both the excitation pressure term modified by the isostatic, inverted barometer (IB) response of the oceans, as well as the wind terms.

The non – tidal oceanic excitation of polar motion is expressed in this study by the regional and global Oceanic Angular Momentum (OAM) series computed from output of the ECCO/JPL ocean model over the period January 1993 – December 2010. That model was forced by atmospheric surface wind stress, heat, and freshwater flux values from the NCEP/NCAR reanalysis. The freshwater fluxes, including evaporation, precipitation, and river runoff fields, are applied as virtual salt fluxes that change the model salinity but that do not add/remove any freshwater mass to/from the model (Greatbatch, 1994; Greatbatch et al., 2001). The model domain spans the globe from 80^oS to 80^oN latitude with 46 vertical levels, a meridional resolution of 1 degree, and a varying latitudinal resolution of 1 degree poleward of 25 degrees that smoothly increases to 1/3 – degree at the equator. Regional values of oceanic excitation functions of polar motion (OAM) were computed at each of the 80640 grid points. The kf080 velocity, temperature, and salinity fields are saved every 10 days, so the OAM computed from them has a 10 – day resolution (the bottom – pressure is saved every 12 – hours). However the fields are saved every 10 days starting from the beginning of each calendar year. The time series are therefore not equi – spaced across calendar year boundaries and must be interpolated to become equi – spaced.

For estimation of the hydrological component of the polar motion excitation function, we use CNES/GRGS EWT fields on a $1.0^o \times 1.0^o$ latitude – longitude grid, produced with 10 – day resolution over the period November 2002 – June 2011. These are EWT fields computed from gravity field models expanded from spherical harmonics between degree 2 and degree and order 50, available every 10 days, using GRACE and LAGEOS data in ITRF2000 (Altamimi et al., 2002). Here the atmosphere – ocean dealiasing product was not added back to the GRACE coefficients, in effect meaning, that atmospheric and ocean effect have been removed. The resulting time – variable gravity field reflects mainly hydrological phenomena, but because it is based on a gravitation signal only, other non-modeled non hydrological effects, such as those resulting from post – glacial rebound or earthquakes, are inherently included. Hydrologic excitation functions are computed from the GRACE EWT fields using the formulae of Eubanks (1993) and Chen and Wilson (2005), from two latitude – longitude grids of water storage, both available from the Special Bureau of Hydrology.

To determine the regional HAM impact on the global signals both AAM and OAM mass and motion terms were removed from the geodetic observations. As discussed below, the regional HAM impact on polar motion excitation is shown to be small. This is consistent with previous studies showing that HAM does not improve the agreement of the geophysical excitation of polar motion (containing contributions from atmosphere and oceans) with geodetic excitation functions (Brzeziński et al., 2009). So HAM contributions are therefore neglected in the subsequent comparisons of residual geodetic signals and regional variations of geophysical excitation functions. That is, to compare the ocean mass term, the geodetic residuals were determined by removing AAM and the current OAM term from the geodetic observations. Similarly, to compare the atmospheric mass term, the geodetic residuals were determined by removing OAM and the wind AAM term from the geodetic observations.

2.2 Fractional covariance

To quantify the relation between regional geophysical and global residual geodetic excitation functions, we compute the amplitude of the fractional covariance defined as:

$$|cov| = \frac{|\sum_{l=1}^{l=n}(\chi_l^R - \overline{\chi}^R)\cdot(\chi_l - \overline{\chi})^*|}{\sum_{l=1}^{l=n}|\chi_l - \overline{\chi}|^2} \qquad (1)$$

where * is the complex conjugate. Here n is the number of points in the time series, overbars represent time averaging, a summation is made over the number of points in the time series, superscript R denotes regional values, terms without superscript are global values of excitation functions, and χ=$\chi_1 + i\chi_2$ denotes the centered complex – valued function. The quantity in Eq.1 is a measure of the contribution of local geophysical signals to the variance in the global residual geodetic series.

In the case of the annual signal, initially the excitation functions of polar motion were bandpass-filtered between 230 – 600 day periods with the use of a higher – order sine zero-phase Butterworth filter with eight poles (Otnes and Enochson, 1972) to remove short and long period oscillations. The method was applied to the χ_1 and χ_2 regional components of AAM, OAM, HAM and residua of the global geodetic excitations of polar motion.

Maps of fractional covariance in the annual band were estimated using a The Fourier Transform Band Pass Filter (FTBPF) around 366 days (360 – 372 days) with parameter λ equal to either 0.0015 for in the case of analyses of AAM and OAM or 0.003 in the case of analyses of HAM. This parameter describes the bandwidth of BPF in the parabolic transfer function (Popiński and Kosek, 1995, Popiński, 1998).

For the analysis in the Chandler band we perform initially a consistent reduction of both the atmospheric, oceanic, hydrological and residual geodetic excitations. With an unweighted least squares fit, we estimate parameters of the model comprising the sum of complex sinusoids with periods +/-1, +/-1/2, +/-1/3 year. Here the sign +/- indicates the prograde/retrograde motion, and the 3rd order polynomial accounting for low – frequency variation. This polynomial harmonic model is then removed from the series. Next, similarly as in the case of the annual, maps of fractional covariance between global and regional signals are estimated using FTBPF in a band centered around 433 days (about 424 – 442 days) for the prograde part of the spectrum. The filter FTBPF was applied to excitation functions expressed in terms of complex valued series $\chi = \chi_1 + i\chi_2$.

3 Results

Here we focus on the contributions of several regions, over two portions of spectral band, of the mass term of the atmospheric, oceanic and hydrological excitation functions of polar motion to the global excitation computed from geodetic data. Overall, the results presented below show that the masses of the liquid and gas envelopes of our planet are not uniformly distributed on the surface of our globe, one consequence of which is the diversity of the contribution of various geographical areas to polar motion excitation. The geographical patterns of the changes of the mass are clearly very different for the atmospheric, oceanic, and hydrological fluids in both considered spectral bands.

The results can be seen in the set of maps of fractional covariances between regional geophysical excitation and global excitation computed from geodetic data. Since the Chandler oscillation is an oscillation of the prograde portion of the polar motion spectrum, we show fractional covariance patterns only for the prograde case.

Figures 1a and 1b show maps of fractional covariance between gravimetric HAM excitation functions and geodetic residuals obtained as a difference between the geodetic excitation function and the sum of OAM and AAM. From Figure 1e we note that the prominent annual signals are due to the monsoonal climates (Fan et al., 2004) situated at latitudes lower than 30^oS. The regions of maxima are located in the Amazon, Central Africa, South Africa, North Australia, and India. Similar structure of variance was noted by Nastula and Salstein, 2011. Maps of fractional covariance remaining after removing seasonal signals from gravimetric and geodetic residuals are scattered above land areas (Fig. 1b). This is probably because the residuals that remain after the seasonal signals are removed have small amplitudes (Nastula and Salstein, 2011). Interestingly, some of the largest locations of fractional covariance in the HAM occur where GRACE results indicate secular changes in the water cycle (Ogawa et. al, 2011).

Figures 1c and 1d show maps of fractional covariance between regional AAM(pressure) and residuals computed as a difference between the geodetic excitation function and sum of OAM(pressure + currents) and AAM(wind). The patterns in the annual band (Fig. 1c) are dominated by a ring-like formation over Asia, the structure of whose variability was shown in earlier studies (Nastula et al., 2003, 2009). The patterns of fractional covariance between the Chandler band have an extended longitudinal formation across the Eurasian continent (Fig. 1 d). The characteristic feature of this pattern are two maxima: one over the North European Plain with the center over the western side of the Central Russian Upland, and the other one over North Asia with the center over Siberia. There also two secondary maxima, one over east coast of US and the other one south of the southern tip of South America

For maps of fractional covariance between regional OAM (bottom pressure) and residuals computed as a difference between the geodetic excitation function and sum of AAM (pressure + winds) and OAM (currents) in the case of the annual oscillation, the covariance magnitude patterns are dominated by changes in the southern Indian Ocean region (Fig. 1e). The Pacific Ocean contributes to the covariance in regions such as: the area just to southwest of the southern tip of South America, in the central area along 30^oS, the large area on the west of Australia ranging from about 20^oS to 50^oS, and variations in the mid – latitude North Pacific. The Atlantic Ocean has a smaller contribution to the covariance but a visible maximum is located between South America and Africa in the mid – latitudes. In the case of the Chandler band, the area that gives the main contribution to the covariance for the prograde term is the southeastern Pacific; one can see the maximum in the Indian Ocean, which, however, is shifted to the southeast in relation to the maximum visible for the case of the annual oscillation (Fig. 1f). Values are also relatively large in the North Atlantic between Greenland and Europe. In addition, the Atlantic has two centers of the covariance in the mid-latitudes in the northern and southern hemisphere. The characteristic of fractional covariances are in agreement with results by Nastula et al. (2012) obtained by covariance, coherence and phase analyses.

4 Conclusions

In this study we compared regional contributions to polar motion excitations determined separately from each of three kinds of geophysical data: atmospheric pressure, oceanic bottom pressure and land hydrology estimated from the Gravity Recovery and Climate satellite experiment.

Our key results of this fractional covariance study in the case of annual term are:

(1)atmospheric pressure – strong variability over the high topography regions of Eurasia and North America,

(2)oceans bottom pressure – strong variability in regions such as the southern Indian Ocean,

(3)land hydrology – the prominent annual signals are situated in the Amazon, Central and South of Africa, North of Australia, India and Indochina.

For the Chandler band we found:

(1) atmospheric pressure – two maxima in the variability one over the North European Plain, with the center over the western side of the Central Russian Upland, and the other one over North Asia with the center over Siberia and two secondary maxima, one over east coast of US and the other one south of the southern tip of South America,

(2) ocean bottom pressure – southeastern Pacific, southern Indian Ocean, and North Atlantic dominate,

(3)land – hydrology maxima are scattered above land areas.

The differences among the geophysical fluids is interesting in itself. However the comparison of fractional covariance maps received from the various geophysical data is made difficult because of the various sizes of applied in the input fields grids. Additionally our comparison was restricted by the fact the gravimetric data covers the much shorter period of time.

The geophysical fluid data sets used here have different spatial resolutions and temporal extent. The differing spatial resolutions required that the data sets be re-sampled to a common grid, thereby introducing interpolation errors to the fractional covariances computed here. The differing temporal extent of the data sets was most problematic for the GRACE-observed HAM series which is only 8-1/2 years long. While this is adequate for analyzing seasonal excitation signals, it is only marginally adequate for analyzing signals in the Chandler band. A HAM data set spanning a much greater length of time is desirable in order to better isolate the Chandler band, thereby reducing the leakage into the Chandler band of signals at nearby frequencies.

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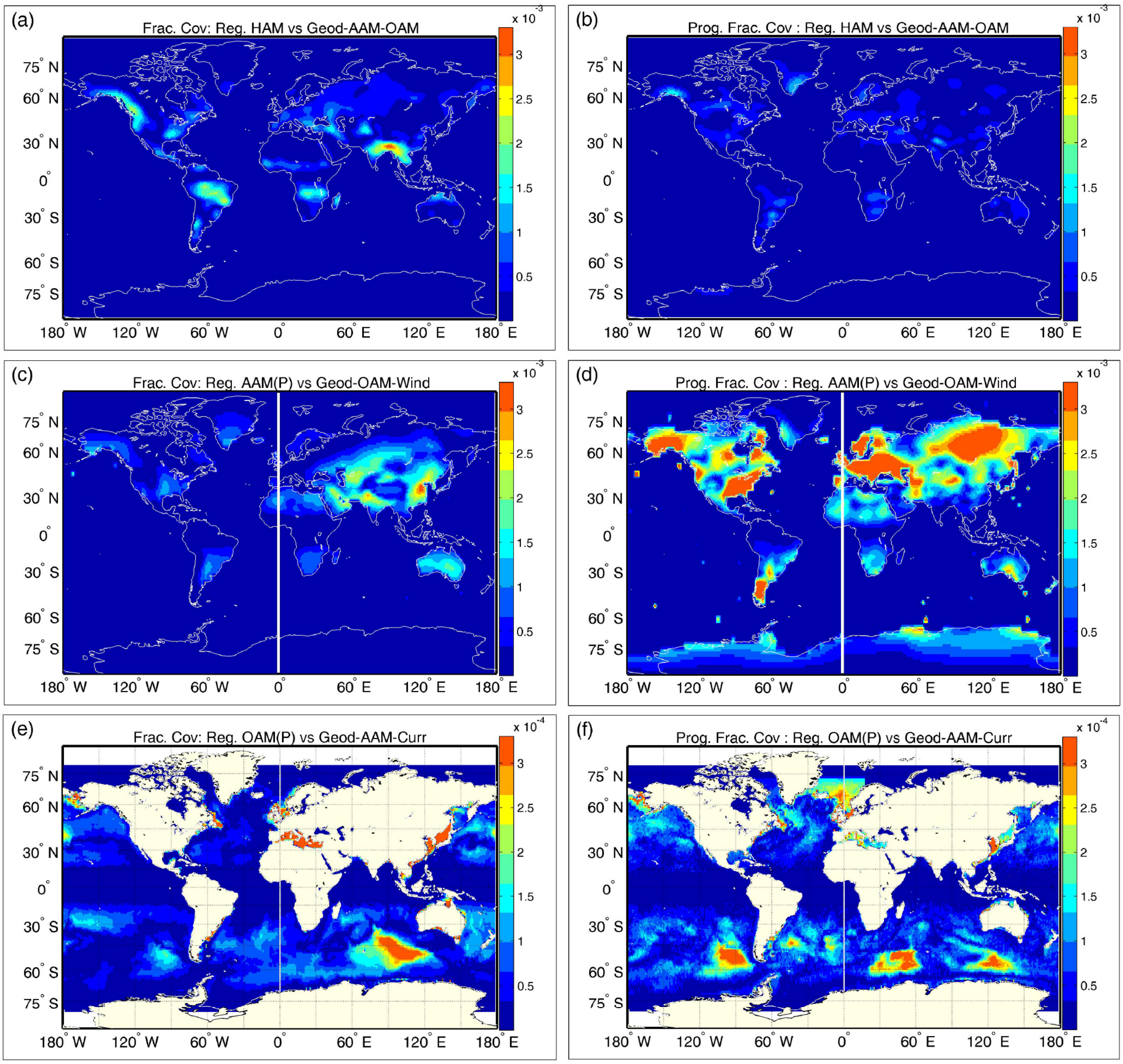

Fig. 1 Maps of fractional covariance (a,b) HAM(bottom pressure) derived from Gravimetric CNES/GRGS data and Geod – AAM – OAM, (c,d) between regional AAM(pressure) and Geod – OAM – Wind, (e,f) between regional OAM(bottom pressure) and Geod – OAM – Currents. The left panels (a,c,e) show maps of fractional covariance for signals in annual band while the right panels (b,d,f) show similar fractional covariance maps but in a band around Chandler oscillation. Maps of fractional covariance are estimated using a FTBPF a with parameter λ which describes the bandwidth of BPF in the parabolic transfer function equal to either 0.0015 for in the case of analyses of AAM and OAM or 0.003 in the case of analyses of HAM. Analyses are made over the periods January 1993 – December 2010 and November 2002 – June 2011 for the AAM,OAM and HAM series respectively Please note that the maximum value on the scale of the (e,f) panels is ten times smaller than on the (a,b) and (c,d) panels.

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